

Particle Production in the Interstellar Medium

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Abstract: The flux of neutrinos and photons originating from cosmic ray interactions with the interstellar medium in the galaxy is calculated based on current models for high energy particle interactions. The contribution from a possible dark matter halo of the galaxy is considered. The photon flux gets a non-trivial attenuation due to interactions with the cosmic background radiation. The neutrino fluxes are compared with those originating from the Earth's atmosphere as well as from active galactic nuclei.

1 Introduction

Cosmic rays of galactic and extra-galactic origin will interact in high energy collisions with the interstellar medium of our galaxy and produce secondary particles [1, 2, 3]. These are mainly mesons that decay and give rise to a flux of muons, neutrinos and photons. The very low density of the interstellar medium imply that the interaction lengths of the secondary particles is long compared to their decay length, such that the mesons will decay before losing energy in secondary interactions. This is also the case for the muons which will decay giving neutrinos. This is the opposite of the situation for cosmic ray particles interacting in the Earth's atmosphere [4], where mesons typically lose energy in interactions before decaying. The fluxes of high energy neutrinos and photons from the interstellar medium could therefore be larger than those from the atmosphere, although the initial production rate of mesons is smaller.

A measurement of these fluxes could potentially give valuable information about the distribution of matter and cosmic rays in the galaxy, which could be of great importance in determining the origin of the cosmic rays. Understanding the flux from the disc of the Milky Way could also be the starting point in a search for baryonic dark matter in a spherical halo around the Milky Way [1, 3].

In addition, these fluxes from the interstellar medium constitute a background in searches for other, more spectacular cosmic sources and must therefore be known in order to extract the desired signal. For example, there is much interest in neutrinos from Active Galactic Nuclei (AGN) (see for example [5] and references therein).

In this paper we present a realistic calculation of the neutrino and photon fluxes to be expected from cosmic ray particle interactions in the interstellar medium. These fluxes are

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derived from complete events obtained by detailed Monte Carlo simulations based on state-of-the-art models for high energy particle collisions. In section 2 we present the model including the cosmic ray energy spectrum, the interstellar matter distribution in the Milky Way and the model for particle production in high energy elementary particle collisions. The resulting fluxes are presented in section 3, where also the attenuation of the photon flux due to interactions with the cosmic background radiation is demonstrated to give a significant effect. Section 4 considers the mentioned dark matter halo and the fluxes that would arise from it. We end, in section 5, with a discussion and comparison with estimated neutrino fluxes from active galactic nuclei.

2 The calculational method

The fluxes of neutrinos and gammas that could be observed at the Earth is basically given by the production rate in the galaxy and the probability that the produced particle reaches the Earth. The fluxes can be expressed as an integral along the line of sight from the Earth ($r = 0$) to the edge of the galaxy ($r = R$)

$$\frac{d\phi_{\nu/\gamma}(E)}{dE} = \int_0^R dr \int_E^\infty dE' \phi_p(E', r) \rho(r) \frac{d\sigma_{\nu/\gamma}(E', E)}{dE} A(E, r) P(r), \quad (1)$$

where the primary cosmic ray flux $\phi_p(E', r)$ is folded with the interstellar matter density $\rho(r)$ and the differential cross section for producing neutrinos or photons. An attenuation factor $A(E, r)$ is also included to account for the loss of flux due to interactions with the interstellar medium and $P(r)$ is the probability that a particle is directed toward the Earth. $A(E, r)$ is calculated separately and folded with the non-attenuated fluxes. Its effect is important for the gamma flux were interactions with the cosmic background radiation producing electron-positron pairs occur.

The integration over r can be greatly simplified since one may calculate the flux from a ‘unit’ column density and then scale with the appropriate integrated density in any given direction. This procedure is possible since the distance between a typical production point r and the Earth is large compared to the decay length for all particles. The energy integral can be obtained based on Monte Carlo simulations of high energy particle collisions giving complete final states including particle decays. For this purpose we have employed the Lund Monte Carlo programs [6].

2.1 The cosmic rays

The flux of cosmic rays in the Milky Way is not well known. The flux measured at the Earth is found to be isotropic to a high degree, the anisotropy being $\lesssim 5\%$ [7]. This isotropy can arise in two ways. First, the bulk of the flux is of extra-galactic origin with a small component from processes in the Milky Way, *i.e.* the flux is universal. Secondly, it is of galactic origin with only a component at the highest energies of extra-galactic origin. The flux at lower energy is in this case captured by the magnetic field of the galaxy and thereby appearing to be isotropic at the Earth. A flux of extra-galactic origin will not be significantly attenuated when passing through the galaxy, since only a few per mill of the cosmic ray particles will interact. This attenuation effect is smaller than other uncertainties concerning the primary flux, and the flux can be treated as homogeneous.

Assuming that the Earth is not at a unique site in the galaxy, it follows that the flux is the same everywhere in the galaxy. Therefore, we assume the flux observed at the Earth to be

uniformly and isotropically distributed throughout the galaxy. The energy dependence of the flux can then be parameterized as [8, 9]

$$\phi_N(E) \left[\frac{\text{nucleons}}{\text{cm}^2 \text{ s sr GeV}/A} \right] = \begin{cases} 1.7 E^{-2.7} & E < 5 \cdot 10^6 \text{ GeV} \\ 174 E^{-3} & E > 5 \cdot 10^6 \text{ GeV} \end{cases} \quad (2)$$

The normalisation is here derived [10] from the directly measured primary spectrum using balloon-borne emulsion stacks in JACEE [11]. It agrees (within some 10%) with more indirectly derived spectra based on measured atmospheric muon fluxes [12], and is also compatible with the data discussed in ref. [13]. The cosmic ray composition is dominated by protons with only a smaller component of nuclei [10, 13].

2.2 The model of the Milky Way

Given the uncertainties concerning the matter distribution in the galaxy, one can only make a fairly simple model for it. However, this should also be adequate for our purpose to estimate the fluxes. Such a model has been used by Domokos *et al.* [1], but it seems to overestimate the column density for high galactic latitudes. Therefore, a model similar to the one in [2] will be used outside the plane of the Milky Way, where the density decreases exponentially with the distance to the galactic plane.

We take the galaxy to be rotationally symmetric in the plane with a radius of 12 kpc and with a constant constant density of 1 nucleon/cm^3 in the plane. Outside the plane, the density decreases as

$$\rho(h) = \rho_0 e^{-h/h_0}, \quad (3)$$

where h is the height above (or below) the disc and $h_0 = 0.26 \text{ kpc}$ is the scale height at the galactocentric distance of the Earth. The Earth is in the galactic plane at a distance of $R_{GC} = 8.5 \text{ kpc}$ from the centre.

Stars are not taken into account in this study, although they affect the fluxes in two ways. First, the cosmic ray particles can interact in the stellar material producing mesons. These will, however, often have secondary interactions due to the relatively higher density environment in the stars. They will thus typically be absorbed or degraded in energy before they decay and therefore relatively less important [1]. Furthermore, the neutrinos and gammas from these meson decays must traverse the star such that photons will be absorbed and also the neutrino flux be significantly attenuated. These aspects are treated in our study [14] of the neutrino fluxes arising from cosmic ray interactions in the Sun. Secondly, neutrino and gamma fluxes from the interstellar medium will be attenuated because of absorption in stars. However, this is a very small effect since the solid angle covered by stars is only $\Delta\Omega/\Omega \lesssim 10^{-10}$ (derived from [1]).

2.3 The model for particle production

To specify the energy spectra of secondaries in cosmic ray collisions with the nuclei of the interstellar medium a model for particle production is needed. With the cosmic rays being predominantly protons and the interstellar matter mainly hydrogen, and only some smaller fraction of heavier nuclei in both cases, the interactions producing the secondary particle fluxes are dominantly proton-proton collisions. Contributions of nuclear collisions can also be treated as nucleon-nucleon interactions, since the nuclear binding energies are negligible and other nuclear

effects have only little influence on the high energy secondary particles that are of interest to us. Therefore, the primary interactions can be taken as proton-proton collisions.

The dominating source of neutrinos and gammas are then the decays of the light mesons (π and K) and muons plus a small contribution from other heavier hadrons. Given the low density of the interstellar medium, secondary interactions are rare and will essentially not happen before unstable particles decay. Therefore, with all light hadrons decaying, the contribution from charmed and heavier particles will not be important as opposed to the case of interactions in the Earth's atmosphere [4]. The dominance of light hadrons (pions) will only disappear above their critical energy ($\varepsilon_{\pi}^{critical} \sim 10^{21} \text{ GeV}$ [1]), where their decay becomes less probable compared to their interaction. Heavy quark production is therefore not explicitly considered in the simulation, but their contribution is estimated based on the spectrum-weighted moment method [4] and shown to be negligible.

The production of light hadrons (not containing heavy quarks) is dominantly through minimum bias hadron-hadron collisions. The strong interaction mechanism is here of a soft non-perturbative nature that cannot be theoretically calculated from first principles, but must be modelled. In the successful Lund model [15] hadron production arise through the fragmentation of colour string fields between partons scattered in semi-soft QCD interactions [6]. The essentially one-dimensional colour field arising between separated colour charges is described by a one-dimensional flux tube whose dynamics is taken as that of a massless relativistic string. Quark-antiquark pairs are produced from the energy in the field through a quantum mechanical tunneling process. The string is thereby broken into smaller pieces with these new colour charges as end-points and, as the process is iterated, hadrons are formed. These obtain limited momenta transverse to the string (given by a Gaussian of a few hundred MeV width) but their longitudinal momentum may be large since it is given by a probability function in the fraction of the available energy-momentum in the string system taken by the hadron. All mesons and baryons in the basic multiplets may be produced and the subsequent decays are fully included. The iterative and stochastic nature of the process is the basis for the implementation of the model in the JETSET program [6]. The parameters in the program were taken at their default values, except that also long-lived particles had to be treated as unstable and their decay simulated.

A non-negligible contribution to the inclusive cross section is given by diffractive interactions. These are also modeled in PYTHIA [6] using cross sections from a well functioning Regge-based approach and simulating the diffractively produced final state using an adaptation of the Lund string model. These diffractive events are included in our simulations and contribute rather less than 10% to the final results.

3 Results

As mentioned, the production rate is only a function of the density since the cosmic ray flux is assumed to be position independent within the galaxy. The energy integral of Eq. (1) has been calculated for a 'unit' column density of $1 \text{ GeV}/\text{cm}^3$ over a distance of 1 kpc ($\sim 5 \text{ mg}/\text{cm}^2$). This was performed by choosing energies between 10^2 and 10^{10} GeV from a flat distribution in $\log_{10} E$, and assigning a weight to account for the detailed form of the primary cosmic ray flux in Eq. (2). Proton-proton collisions at these energies were then simulated using PYTHIA [6] resulting in complete events. After all particle decays, neutrinos and photons were recorded and filled in energy-histograms applying the weight for the event.

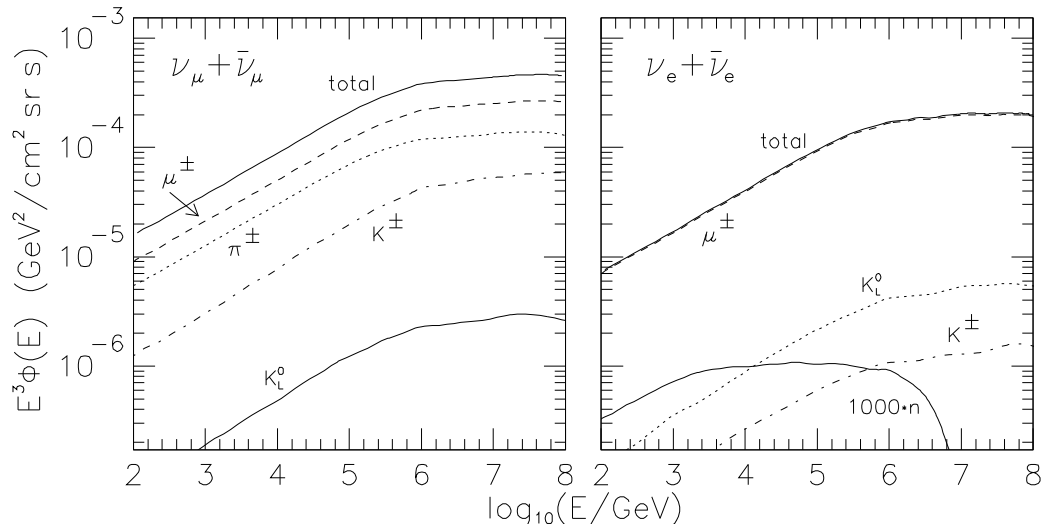


Figure 1: The E^3 -weighted flux of muon and electron neutrinos from interactions of cosmic rays with the interstellar medium in a column of length 1 kpc and density 1 nucleon/cm³. The total flux is shown (full curve) as well as the contributions from the decay of the indicated particles.

3.1 The neutrino fluxes

The resulting fluxes of muon and electron neutrinos are shown in Fig.1. For muon neutrinos the dominating source is muon and pion decay, while for electron neutrinos muon decay dominate strongly with only a few per cent from kaon decay and a totally negligible fraction from neutron decay.

This is rather different from the other sources of cosmic ray induced neutrinos in the vicinity of the Earth, *i.e.* the Sun's and the Earth's atmosphere. In case of the Earth's atmosphere the distance involved is so short that the muon can be considered almost stable. The most important sources of muon (electron) neutrinos are therefore the decays of pions and kaons (kaons), with charmed particles being the dominating source at very high energies [4]. A comparison with these atmospheric fluxes is made below in section 5 (Fig.6). For the Sun, muons cannot be considered stable, and give a significant contribution to the fluxes. The muons, however, loses energy through electromagnetic interactions and are therefore less important at higher energies compared with the light mesons [14].

Because of the small cross section for ν -hadron and ν - γ interactions, the ν -fluxes will not be noticeably attenuated due to interactions with the interstellar medium or the cosmic microwave background. The attenuation due to interactions with stellar material is also negligible since, as mentioned, the stars cover only a very small solid angle.

3.2 The photon flux

As opposed to the neutrino fluxes, the photon or gamma flux is attenuated by interactions. Photons of very high energy can interact with the cosmic microwave background to produce particles. Unless the energy is extremely high, one need only consider electron-positron production, *i.e.* $\gamma\gamma \rightarrow e^+e^-$.

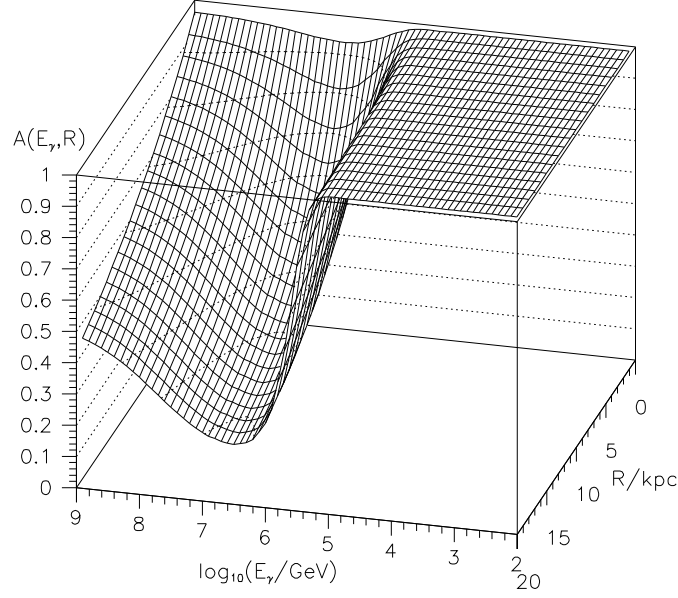


Figure 2: The attenuation factor, Eq. (6), for the photon flux as a function of the photon energy E_γ and the distance R from the Earth to the edge of the galaxy.

The cosmic microwave background is isotropic and has an energy spectrum given by

$$\frac{dn(E)}{dE} = \frac{1}{\pi^2(\hbar c)^3} \frac{E^2}{\exp(E/kT) - 1} + \Theta(10^{-5} - E) \frac{3.3 \cdot 10^7}{E}, \quad (4)$$

with E in eV . The first part is the thermal background spectrum at temperature T and the second part is a very simple parameterisation of the radio-wave background at very low energy [16]. The latter is far from as accurately known as the former, but since it only influences the flux above $\sim 10^7 GeV$ it is not of significant importance for our purposes.

To calculate the attenuation one needs to account for both the energy-spectrum of the background radiation and the angle between the two photons. We do this by defining an effective thickness ($mbarn/cm^3$) given by

$$\langle \sigma n \rangle (E_\gamma) = \frac{1}{4\pi} \int_0^{2\pi} d\phi \int_{-1}^1 d(\cos\theta) \int_{E_{th}(\theta)}^\infty dE \frac{dn(E)}{dE} \sigma^{\gamma\gamma \rightarrow \ell\bar{\ell}}(2E_\gamma E(1 + \cos\theta)), \quad (5)$$

where ϕ and θ are the azimuthal and polar angles between the interacting gammas in the galactic ‘laboratory system’. $\frac{dn(E)}{dE}$ is the cosmic background radiation in Eq. (4) and $\sigma^{\gamma\gamma \rightarrow \ell\bar{\ell}}(s)$ is the cross section for charged lepton pair production as a function of the CM-energy \sqrt{s} , which we have calculated. It is sufficient in this context to use the leading order formula for this cross section and to consider e^+e^- production only. The threshold energy for a microwave background photon is $E_{th}(\theta) = 2m_\ell^2/E_\gamma(1 + \cos(\theta))$ in terms of the energy E_γ of the incoming photon.

Since the production of photons is isotropic along the line of sight within the plane of the Milky Way an attenuation factor can be derived and applied to the flux obtained from the Monte Carlo simulation. The attenuation factor is obtained by integrating over the line of sight and weighting each production point with the probability ($e^{-R\langle\sigma n\rangle}$) that a produced photon reaches the Earth,

$$A(E_\gamma, R) = \frac{1}{R \langle \sigma n \rangle (E_\gamma)} (1 - e^{-R \langle \sigma n \rangle (E_\gamma)}) \quad (6)$$

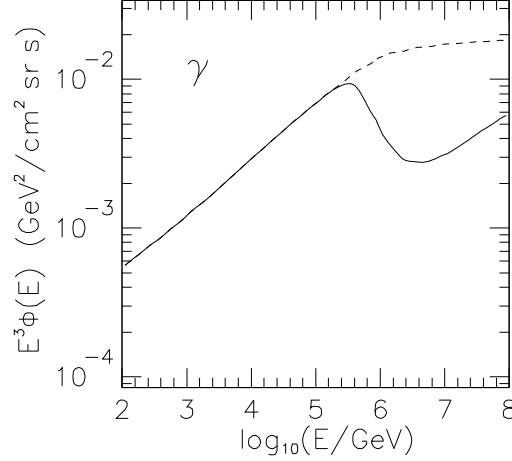


Figure 3: The attenuated (solid line) and unattenuated (dashed line) E^3 -weighted flux of photons from interactions of cosmic rays with the interstellar medium of density 1 nucleon/cm^3 integrated over the whole Milky Way in the direction to its center.

where R is distance to the edge of the Milky Way. A numerical evaluation of this factor is shown in Fig. 2. The dip structure in the attenuation factor is a consequence of folding two peaked functions. The cosmic microwave background radiation which peaks at $T \sim 7 \text{ K}$, and the electron-positron production cross section peaked at $s \sim 13 m_e^2$.

With this attenuation factor, we then obtain the attenuated photon flux shown in Fig. 3 and compared to the unattenuated flux; both are in the direction towards the centre of the Milky Way. The attenuation dip structure is obviously a reflection of the structure in Fig. 2. Another such dip structure would also appear at an energy of $(m_\mu/m_e)^2 10^{6.5} \text{ GeV} \approx 10^{11} \text{ GeV}$, when the reaction $\gamma\gamma \rightarrow \mu^+\mu^-$ becomes energetically possible. For such high energies is, however, our parameterisation of the primary flux inadequate and our method therefore no longer applicable.

3.3 Parameterisation of the fluxes

The resulting fluxes can be parameterised in a form inspired by the analytic formalism used by Berezhinsky *et al.* [2]. The photon flux, which is attenuated through pair production as discussed, is better treated in two steps; one for the production and one for the attenuation. The non-attenuated fluxes are parameterised as

$$\phi(E) = \begin{cases} R\delta N_0 E^{-\gamma-1} & E < E_0 \\ R\delta N'_0 E^{-\gamma'-1} & E > E_0 \end{cases} \quad (7)$$

with the fitted parameter values given in Table 1. (N'_0 is not fitted, but given by the continuity condition at E_0 .) $R\delta$ is the column number density, δ is the average number density in nucleons/cm^3 and R is the distance to the edge of the galaxy in kpc . By inserting the corresponding values from our model, or another model, of the galaxy one can obtain the fluxes from this parameterisation. Results are shown in section 5 and discussed in connections with other sources.

particle	N_0	γ	E_0	γ'	N'_0
$\nu_\mu + \bar{\nu}_\mu$	$3.0 \cdot 10^{-6}$	1.63	$4.7 \cdot 10^5$	1.95	$1.9 \cdot 10^{-4}$
$\nu_e + \bar{\nu}_e$	$1.3 \cdot 10^{-6}$	1.63	$4.2 \cdot 10^5$	1.95	$8.3 \cdot 10^{-5}$
γ	$4.7 \cdot 10^{-6}$	1.63	$7.6 \cdot 10^5$	1.94	$3.1 \cdot 10^{-4}$

Table 1: Values of the parameters in Eq. (7) obtained from fits to the neutrino fluxes in Fig. 1 and the unattenuated photon flux in Fig. 3.

The attenuation factor $A(E, R)$ can be obtained from Eq. (6) using the effective thickness parameterised as

$$\log \{ \langle n\sigma \rangle (E_0) \} = -25.34 + 6.82 \sqrt{\log E_0 - 4.99} e^{-0.29(\log E_0 - 4.99)} \quad E_0 > 10^5 \text{ GeV} \quad (8)$$

whereas for $E_0 < 10^5 \text{ GeV}$ the pair production cross section negligible small and the attenuation factor effectively unity, see Fig. 2.

4 Fluxes from a possible dark matter galactic halo

Cosmic rays could also interact with matter in a galactic halo and, depending on the properties of this matter, give a neutrino flux of interest. If the halo matter consists of weakly interacting massive particles (WIMPS) the interaction cross section is very small and would give a negligible neutrino flux. However, with dark matter of hadronic nature this source could give a measurable flux. In the scenario of massive cold halo objects (MACHO's), the interactions would take place in objects of high density. The interaction lengths of the produced secondary mesons would then be shorter than their decay lengths such that they would lose energy or be absorbed before decaying into leptons. This would result in a lepton flux at very low energies only, which at the Earth would have to compete with the high atmospheric flux. Recent measurements by the MACHO collaboration [17] show, however, that these objects can only make up $\sim 20\%$ of the dark matter. This leaves the possibility for a gaseous hadronic component of the dark matter as discussed by De Paolis *et al.* [3]. They calculate gamma ray fluxes in the energy range $1 - 10^6 \text{ GeV}$ from decays of π^0 's produced in cosmic ray interaction.

Following the approach of De Paolis *et al.* [3] we have calculated the corresponding neutrino fluxes. The gaseous hadronic matter distribution in the halo is assumed to be of the form

$$\rho(R) = \rho_0 f \frac{a^2 + R_{GC}^2}{a^2 + R^2}, \quad (9)$$

where $\rho_0 \approx 0.3 \text{ nucleons/cm}^3$ is the local dark matter density and $f \sim 0.5$ is the fraction of dark matter in form of gaseous nucleons. R is the distance from the galactic centre to an arbitrary point and $R_{GC} \sim 8.5 \text{ kpc}$ to the Earth, whereas $a \sim 0.5 \text{ kpc}$ is the galactic core radius.

The flux of cosmic rays in the halo may consist of two parts. First, particles that escape from the disc, which probably give a flux that decreases in the same way as the halo density does, *i.e.* Eq. (9), unless it is confined by some unknown mechanism. Secondly, there may be a flux of extra-galactic origin, which can be assumed to be isotropic. De Paolis *et al.* [3] do not consider energies higher than 10^6 GeV and are therefore dominated by the first part. The normalisation can then be estimated from theoretical arguments [18] resulting in $\sim 1/500$ times that at the Earth. Thus we have the cosmic ray flux in the halo

$$\phi_p(E, R) = \frac{\phi_{p,\oplus}(E)}{500} \frac{a^2 + R_{GC}^2}{a^2 + R^2}. \quad (10)$$

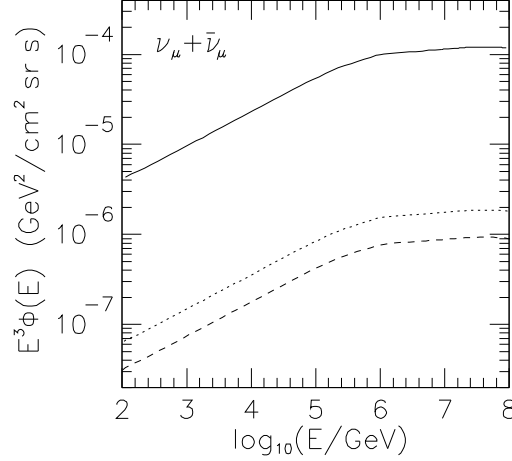


Figure 4: *The E^3 -weighted flux of muon neutrinos from a possible dark matter galactic halo induced by interactions of cosmic rays of galactic (dashed line) and extra-galactic (dotted line) origin. Shown for comparison is also the flux from the normal interstellar medium (section 3.1) at high galactic latitudes (solid line).*

Part of this flux is directed away from the galaxy such that the secondary flux will not reach the Earth. This could be accounted for by an efficiency factor, but since it is unknown it is not taken into account.

The fluxes of neutrinos are then obtained by folding the cosmic ray flux and the halo density and integrating the production along the line of sight analogously to the galactic flux (Eq. (1)). The resulting flux is shown by the dashed curve in Fig. 4 and seen to be significantly smaller than the galactic flux at high latitudes (where it is lowest). One should remember that this flux from the halo is a crude estimate and may be seen as an upper limit due to the mentioned neglect of the efficiency factor.

Extra-galactic cosmic rays are also believed to contribute to the flux in the halo, especially at very high energies. The normalisation of this component is unknown, but could be as high as given by the high energy flux at the Earth. In order to compare with the flux induced by cosmic rays escaping from the galaxy, we take the normalisation to be same as in Eq. (10),

$$\phi_p(E, R) = \frac{\phi_{p,\oplus}(E)}{500}. \quad (11)$$

The neutrino flux is here obtained in the same way as above, and shown by the dotted curve in Fig. 4.

Although it seems that the flux from the halo cannot compete with that from the galactic disc, it is still conceivable that its magnitude is significantly higher than here estimated. This would happen if the primary cosmic rays are completely of extra-galactic origin and therefore the same as that at the Earth, *i.e.* Eq. (11) reduces to $\phi_p(E, R) = \phi_{p,\oplus}(E)$. This would give a neutrino flux that is about a factor five higher than the corresponding interstellar flux. Although, such high extra-galactic flux is not probable, a higher flux than in Eq. (11) is not unrealistic.

From the above discussion, the prospects for detection of a dark halo based on neutrino flux measurements does not look promising. In particular, this flux is considerably lower than the atmospheric flux [4] and the estimated one from active galactic nuclei, as discussed in section 5 (Fig. 6).

5 Concluding discussion

The neutrino fluxes shown above in Fig. 1 are given for our basic ‘unit column’ of interstellar matter. Using these one may obtain the integrated flux from any direction. In Fig. 5 we show our resulting muon neutrino flux (full curves) from the direction towards the center of the Milky Way (highest flux) and orthogonal to the galactic plane (lowest flux). In Fig. 5a we compare with the original results of two earlier calculations by Domokos *et al.* [1] and by Berezhinsky *et al.* [2]. The differences between these curves are mainly related to the different assumptions concerning the interstellar matter density profile and the normalisation of the cosmic ray spectrum. Thus, they illustrate the uncertainty due to these inputs to the different calculations.

In order show other differences between these different calculations we have recalculated the results of [1] and [2] using their formalisms but with our density and cosmic ray parametrisations. The results are shown Fig. 5b and demonstrate a close agreement for energies up to 10^5 – 10^6 GeV. At higher energies there are, however, significant differences due to the treatment of the change in slope of the cosmic ray spectrum, *cf.* Eq. (2). In [2] energies above the ‘knee’ are not considered, and the naive extrapolation to higher energies results in an overestimated flux. About a factor three excess at the highest energies is expected based on an estimate using the analytic method with spectrum-weighted Z -moments [4, 8, 19], in agreement with the effect seen in Fig. 5b. In [1] this change of slope is included, but its effect on secondary particles cannot be fully taken into account since their calculation is based on an analytic method. One must here make assumptions about from what average primary energy a given neutrino comes, and thereby specify how the ‘knee’ from the change in the cosmic ray energy spectrum is transported into a ‘knee’ in the final neutrino spectrum. This problem does not occur in our Monte Carlo method, since the neutrino spectra are here obtained through an event-by-event simulation taking the fluctuations into account. Our results are therefore more reliable in this respect.

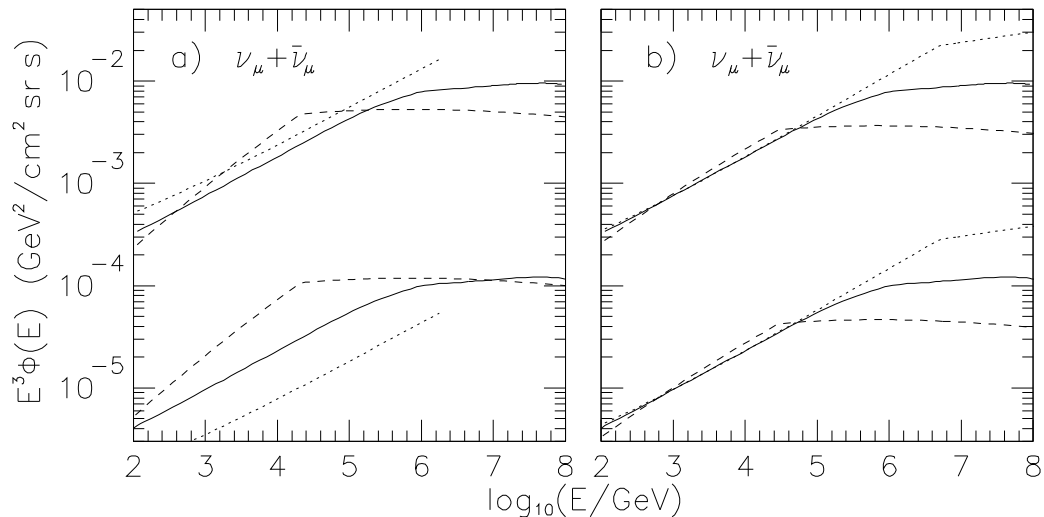


Figure 5: The E^3 -weighted fluxes of interstellar muon neutrinos in the direction towards the center of the Milky Way (upper set of curves) and orthogonal to the galactic plane (lower set of curves). Comparison of our results (full lines) with those by Domokos *et al.* [1] (dashed lines) and by Berezhinsky *et al.* [2] (dotted lines). In (a) the original results are used, whereas in (b) the results of [1] and [2] are modified to have the same galactic density profile and cosmic ray flux as in our calculation.

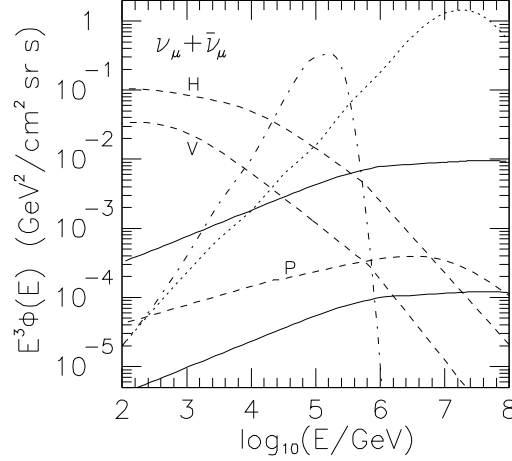


Figure 6: E^3 -weighted fluxes of muon neutrinos at the Earth from cosmic ray interactions with the interstellar medium looking towards the galactic centre (upper solid curve) and orthogonal to the galactic plane (lower solid curve) as calculated in this study, and the flux from the Earth's atmosphere in the vertical (V) [4] and horizontal (H) [20] direction originating from conventional π, K -meson decays as well as from prompt (P) charm decays [4]. For comparison, the diffuse flux of muon neutrinos from active galactic nuclei as predicted in [21] (dotted line) and in [22] (dash-dotted line) are shown.

There is also a contribution to the interstellar flux from semileptonic decays of charmed and heavier hadrons. We have estimated this based on the analytic method with spectrum-weighted moments [4, 8, 19] using our previously calculated Z -moments for charm particle production and decay [4]. Taking also the contribution from muon decay into account, we find a muon neutrino flux which is only contributing about $2 \cdot 10^{-4}$ to the interstellar flux and a factor two higher contribution for the electron neutrino flux (due to a lower interstellar electron neutrino flux). The smallness of this charm contribution justifies the neglect of it in our Monte Carlo treatment.

From Fig. 5, and these considerations, one can also conclude that the uncertainties originating from the particle physics input are not larger than other uncertainties. Our Monte Carlo calculation also confirms that the approximation done with the analytic method are justified except at the highest energies where special precautions must be taken.

The fluxes from the interstellar medium should be compared with those from other sources in order to establish their observability and their significance as a primary interest of study or as a potential background. This is done in Fig. 6 where our result on the muon neutrino flux is compared with those from cosmic ray interactions in the Earth's atmosphere and with two predictions of the diffuse flux from active galactic nuclei. The interstellar flux is seen to be considerably lower than the atmospheric flux, except at the highest energies. It will therefore be very hard to observe with detectors on the Earth. At the highest energies considered, the interstellar flux is of comparable magnitude as the prompt atmospheric flux (from charm decays). The latter is almost direction independent up to $\sim 10^7$ GeV such that the curve shown for the vertical direction applies in essentially the whole energy range; the horizontal flux being slightly higher for the highest energies only. Given the small absolute scale of the fluxes at these energies, the event rate will be very low in the neutrino telescopes currently under construction. The interstellar flux becomes important compared to the vertical atmospheric flux only at energies

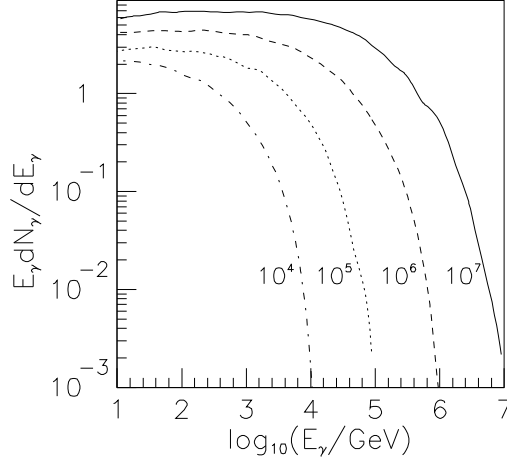


Figure 7: *Energy-weighted spectrum of photons from interactions of cosmic ray particles, having the specified energies, with the interstellar matter (i.e. the photon yield).*

above 10^4 GeV . The corresponding event rate in a detector of $3 \cdot 10^4 \text{ m}^2$, *e.g.* AMANDA, would be $\sim 0.5/\text{year}$ in a cone of opening angle 10° directed towards the centre of the Milky way.

Our calculated neutrino flux from the interstellar matter is significantly lower than the one from active galactic nuclei, as demonstrated in Fig. 6, and should therefore not be a problematic background for this extra-galactic source. On the other hand, the atmospheric neutrino flux will be problematic in this context, since it dominates in the lower energy range. At high energies where the atmospheric flux is lower, the absolute rate is very low.

Concerning the flux of electron neutrinos the situation is very similar to the case of muon neutrinos, except that the atmospheric background is significantly lower [4] and the interstellar flux is a factor ~ 2 lower than the corresponding muon neutrino flux (Fig. 1). Since the dominating production process in AGN is decays of pions followed by the decays of the muons, the electron neutrino flux from AGN's should also be a factor ~ 2 lower. Thus, the relative fluxes from these sources should be the same as for muon neutrinos. There is, however, no good technique to detect high energy electron neutrinos, so the prospects to search for such a signal is worse.

The yield of photons in cosmic ray interactions with the interstellar matter has been considered before, *e.g.* by Berezhinsky *et al.* [2]. Our corresponding result obtained from the unattenuated photon flux in section 3.2 is shown in Fig. 7. It is about a factor two higher than that of [2], mainly due to the higher π^0 multiplicity in our complete event simulations. The gamma flux can be used to set limits on the cosmic ray flux and the matter distribution in the galaxy. The experimental situation is here, however, quite different from the case with the neutrino flux. The gammas are detected either directly on satellite based experiments or with ground based air shower arrays. The signal rate will be higher than with neutrinos due to the larger interaction cross section. The flux of gammas is, however, very small ($\sim 10^{-4}$) compared to the inclusive cosmic ray flux dominated by protons. Differences in the air showers produced by gammas and hadrons may allow access to information on the gamma flux.

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